AN EFFICIENT OPTICAL OBSERVATION GROUND NETWORK IS THE FUNDAMENTAL BASIS FOR ANY SPACE BASED DEBRIS OBSERVATION SEGMENT

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ABSTRACT

A matter which is strongly debated in the SSA Community, concerns the observation of Space Debris from Space [1]. This topic has been preliminary studied by our Team for LEO, MEO and GEO orbital belts, allowing to remark a fundamental concept, residing in the fact that to be suitable to provide a functionality unavailable from ground in a cost to performance perspective, any Space Based System must operate in tight collaboration with an efficient Optical Ground Observation Network. In this work an analysis of the different functionalities which can be implemented with this approach for every orbital belt is illustrated, remarking the different achievable targets in terms of population size as a function of the observed orbits. Further, a preliminary definition of the most interesting missions scenarios, together with considerations and assessments on the observation strategy and P/L characteristics are presented.

1 INTRODUCTION

Compagnia Generale per lo Spazio (CGS SpA), formerly Carlo Gavazzi Space, has consolidated an Italian Consortium, comprising the Mathematics Department of Pisa's University (DM), Space Dynamics Services (SpaceDyS), the Institute for Applied Physics (CNR-IFAC) and the Italian National Institute for Astrophysics (INAF), which has a recognised experience on SSA problematic. In this framework many SSA topics have been successfully studied and innovative solutions have been proposed, opening the way to successful applications [2][3].

In this framework the opportunity to implement a Space based concept for the observation of Space Debris has been preliminary analysed by our Consortium in order to clearly define all pros and cons related to a Space Based Space Debris Observation System and to precisely define the conditions under which such a system can become an interesting solution to solve SSA problematic arguments.

A basic statement which results clear at a first simple analysis is that a Space element cannot in any case entirely replace, in a cost-effective way, the ground element. The main reasons are mission time duration and observation timeliness. A ground-based telescope/radar can be operational, with maintenance, for 20 and more years. A satellite with a guaranteed lifetime longer than 5 years is already very expensive. Moreover, the timeliness requirements for a SST system are very tight, of the order of 1-2 days allowed between re-observation of each object already identified. Thus a space-based segment capable of working alone, without any support from a ground element, would need a constellation of several S/C to guarantee timeliness in the observation of all objects, and a replacement every 4-5 years.

From the above considerations, it follows that, among the list of functions a system must perform to catalog debris, the ones which are best suited for a space segment are the initial ones, that is the very first observations and the early stages of correlation, in particular the one called 'cold start' or 'linkage', that is the process leading to the very first full orbit.

On the contrary, the follow up observations are more effectively and economically performed from the

Ground, due to both easier pointing accuracy – as compared to the effort required from Space, not only considering the P/L but also the class of the required Satellite platform and volume data handling. A space-based sensor simply replacing either a ground-based sensor or even a software component for correlation, without introducing an improvement in the performances obtained from Ground, is obviously a waste.

In the following an analysis of a feasible strategy allowing to justify the application of a Space Based System is outlined and assessed.

2 PRELIMINARY ASSESSMENT OF THE EXPECTED SPACE BASED OPTICAL OBSERVATION PERFORMANCES

The driving parameter allowing to assess whether an object can be detected or not by means of an optical observation, i.e. by collecting an image of the portion of the sky where it resides during a certain time lapse, is the value of the Signal to Noise Ratio (SNR) registered in the image pixels upon which the object insisted during the image collection period.

Many parameters affect this value depending on:

a) the object luminosity, which can be assessed by evaluating the object apparent V_{mag} at the observation time. This parameter is affected by many physical parameters concerning both the object itself (such as the object size, the object distance from the observation point, the object albedo, etc.) and the observation geometry (e.g. phase angle, trailing loss, etc.)

b) the observation conditions (exposure time and consequent Poisson's statistical noise, sky background noise, etc.)

c) the optical characteristics of the optical system adopted to collect the image, establishing the net flux of photons arising from the object surface and finally impinging in the sensitive area of the detectors that register the object image (such as entrance aperture, F-number, pixel scale, optical efficiency, obstructions, psf dimensions, etc.)

d) the characteristics of the detector applied for image collection (e.g. pixel size, dark current, read out noise, binning, cosmetics, etc.)

It is evident that the above reported list comprises the fundamental elements allowing to define the P/L requirements and is necessary to properly preliminary select its constituting elements.

The detailed evaluation of the above reported parameters allows to assess the SNRs expected from a target object once its observation conditions are set and the optical observation apparatus has been defined.

A preliminary evaluation is possible in this view by developing a model of the observation, taking into account the main elements contributing to the formation of the Signal to Noise ratio values as a function of the observed object apparent magnitude V_{mag}. By introducing different observation parameters it is then possible to calculate the expected SNR.

In particular different pixel scales and entrance aperture diameters are considered, as parametric variables, in order to preliminary define the P/L characteristics necessary to detect different classes of objects.

This way one can assess the expected SNR for objects characterised by different apparent magnitudes, when CCDs are applied as detector elements, with the following parameters

- Detector QE = 0.55 (mean value over the whole visible spectral segment)
- R/O Noise = 25e-/pix
- Dark Current = 6 pA/cm^2 @ 25°C
- Detector Operating Temp = -55°C
- Filter Band = clear band
- Optical Efficiency = 0.8
- Sky Background = 21.5 V_{mag}/arcsec^2

and by considering, for the case of un-binned pixels, different exposure times, different F-numbers (giving rise to different pixel scales), as well as different entrance diameters. Of course no seeing effects are present in space, an important factor allowing to improve the SNR.

It must be remarked that the pixel scale parameters have been selected considering the limitations encountered on board of a Space Based apparatus, both due to pointing stability and data volume handling capability.

The obtained results are reported in Tab. 1, where SNR values lower than 3 are remarked, as a SNR = 3 is considered as a threshold value, effective to allow detection of the observed object.

It is clear from Tab. 1 that:

a) the major drivers determining whether a faint object is detectable or not are represented either by the telescope entrance diameter or by the exposure time,

b) medium-high class constituting elements (optical efficiency, detector efficiency, etc.) must be applied in order to guarantee the sufficient detection capability, without requiring the introduction of inconvenient aperture diameters,

c) the optimal optical P/L size is strongly related to the orbital belt characteristics.

Table 1. Expected SNR values as a function of the P/L entrance diameter (D), pixel scale (PS) and exposure time (t), for different object apparent magnitude values (V_{mag}). In particular two PS cases, 4.4"/pix and 3.0"/pix. respectively, are reported with the expected SNR values, for different telescope apertures and exposure times (1s and 10s respectively). SNR values remarked in dark yellow are lower than the threshold value 3, considered as minimum to detect the object.

PS = 4.4"/pix D (mm)	V_{mag}	SNR Exposure Time t = 1s	t = 10s	PS = 3.0"/pix D (mm)	V_{mag}	SNR Exposure Time t = 1s	t = 10s
200				200			
	19	0.577	4.572		19	0.584	4.929
	18	1.426	10.433		18	1.441	11.091
	17	3.443	21.848		17	3.477	22.778
	16	7.927	41.296		16	7.994	42.264
300				300			
	19	1.248	8.352		19	1.278	9.379
	18	3.030	18.303		18	3.098	19.940
	17	7.054	36.344		17	7.188	38.275
	16	15.222	65.507		16	15.434	67.232
400				400			
	19	2.109	12.218		19	2.192	14.098
	18	5.023	26.144		18	5.199	28.885
	17	11.265	50.533		17	11.577	53.476
	16	23.034	89.210		16	23.451	91.665
500				500			
	19	3.109	16.047		19	3.283	18.845
	18	7.261	33.859		18	7.608	37.714
	17	15.756	64.486		17	16.308	68.414
	16	30.928	112.644		16	31.577	115.811
600				600			
	19	4.203	19.824		19	4.508	23.551
	18	9.642	41.466		18	10.216	46.420
	17	20.350	78.286		17	21.184	83.177
	16	38.769	135.929		16	39.659	139.794

3 SURVEYING AND TASKING SNR BASED STRATEGY

For a given telescope performance, the Signal S depends upon the ratio d^2/r^2 (where d is the mean diameter of the debris observed surface and r the distance), upon the trailing loss parameter T (defined as the length in pixels of the trail for a given exposure time) and upon the phase φ (defined as Sun-Debris-Observer angle).

Given the enormously superior cost, both for procurement and operations, of a space-based telescope with respect to a ground based one of the same size, if the quantities r, T and φ were the same - or such that the SNR turns out to be the same for the same diameter d - the choice of a Space-based sensor would be unjustified.

The parameters r and φ must be considered in combination: the apparent magnitude of an object

observed at a given phase φ degrees can depend upon the object albedo and surface characteristics, but we can use as reference a well-known model used for asteroids - corresponding to a value 0.15 of the slope parameter G [4] - for which $\varphi = 90$ deg corresponds to an increase by 2.1 magnitudes, that is a loss by a factor 6.9 in signal, equivalent to a change in r by a factor 2.6. The value $\varphi = 120$ deg corresponds to a loss of 3.6 magnitudes, that is a factor 27.5, which could be compensated by a decrease in r by a factor 5.25.

The trailing loss T is the most interesting parameter to discuss the Ground/Space telescope trade off. In general the value of T is much larger for a Space-based telescope, because of two effects: 1) the velocity of the space platform contributes to the relative velocity, thus to the angular velocity; 2) if a smaller value of r is used to improve the SNR, then the value of T grows proportionally to $1/r$. Smaller values of the relative velocity, thus of T, can be obtained from space only if the target debris is on a similar orbit, where 'similar' implies not just similar semi major axis and eccentricity, but even more similar orbit plane.

The SNR loss due to trailing T is of the order of $1/T$ if the trails are detected by sufficient SNR on each pixel, but can be enhanced of the order of $1/(2 \sqrt{T})$ if the trail is detected by an advanced image processing averaging on all possible trails [5]. Some typical values of T for a ground based telescope with a pixel scale of 1.5 arcsec/pixel are 600 for a low LEO, 200 for a high LEO (both with 1s exposure), 200 for a MEO (with 10 s exposure); all these values are obtained by assuming sidereal pointing [2][3]. From this numbers it is clear that the lack of an advanced image processing results in an inacceptable degradation of the sensor performance.

For GEO, with the simple method of stopping the motor driving the motion in right ascension of the telescope, the values of T could range between 1 and 60 (for a 10 s exposure), with the highest values for non-resident GEO such as GTO; thus for resident GEO trail detection is much simpler, and even longer exposures can be used easily.

For space based telescopes the values of T depend from the pixel scale, which is expected to be larger than the ones to be used on the ground, because of the much larger cost of producing, processing and/or transmitting large image files in space.

Nevertheless, given that angular velocities between comparatively near satellites are of the order of 1 degree per second, with even higher peaks for the contra-rotating targets, at a first sight there are few possibilities for finding a favourable trade off in terms of SNR between a small telescope in space (telescope diameter D in the range 20-40 cm) and a larger telescope on the ground ($D = 100$ cm, [2]). Some cases can be excluded straight away: to observe higher

objects, like MEO and GEO (but also NEO) from LEO cannot work in this perspective, because a LEO orbit is not any closer than a ground station - r is about the same - the phase cannot be very different and there is no way to get a lower angular velocity than the one from the ground, thus the telescope diameter required from space is about the same, apart from advantages due to darker background and no atmospheric absorption, which are by no means enough to compensate for the smaller size for space-based due to cost consideration.

On the contrary the above analysis suggests a way forward for the design of a space-based element, provided it is not forgotten that the target design is for an integrated system containing both Ground-based and Space-based elements. In fact, the process of cataloguing the orbits of a population of space debris includes at least three steps.

1) there is a survey phase, in which new objects are 'discovered', without prior knowledge of their position and angular velocity on the celestial sphere, that is observed multiple times at such intervals that correlation is possible and a preliminary 6-parameter orbit can be computed

2) there is a confirmation phase in which the same object can be recovered by targeted follow up (also called, in different context, tasking or tracking)

3) the orbit computed by least squares fit to the observations of 1) and 2) needs to be maintained, by re-observing often enough to maintain the accuracy envelope needed to predict possible coincidence with the targets in its orbit region.

For step 2 it is already possible to predict the position and angular velocity of the object whose orbit was generated by step 1), although as a general rule of thumb the position is weakly constrained, thus requiring a wide field telescope/radar for follow up.

On the contrary, an interesting result obtained during the ESA SARA study [2] was that the predictions of the angular velocity are pretty good, to the point that the telescope/radar could be used in tracking mode, that is moving in a way different from sidereal pointing, to obtain a decrease of the trailing parameter to $T = 1$. This result suggest then that the tracking sensor can obtain a better SNR by a factor of the order of 10.

In conclusion, for Ground based telescopes the tracking mode can allow to follow up objects which are a factor about 3 smaller in diameter than the ones which can be discovered by the same telescope when used in survey.

On the other hand, the same method to improve the performance in tracking mode is not easy to apply to space-based telescopes. Either there is a telescope

mounted on gimbals, with two degrees of freedom, or the pointing of the telescope to a specific direction and with a given angular velocity requires to change frequently the attitude of the S/C. This appears to be incompatible with a competitive cost of the Space element. Moreover, it is not clear from the above reported simple considerations that such Space Based Tracking is actually required to achieve correlation.

Before drawing a general conclusion on the best way to cooperate between a Ground-based network and a Space-based constellation, we need to analyse the exceptions cited above of Space-based optical observations with low angular velocity. Since not just semi-major axis and eccentricity but also the orbital plane need to be similar, for segments of the debris population which are widely dispersed in orbital plane the 'co-rotating' debris with small angular velocity are a small fraction; even in the Sun-synchronous group of orbits. Although the distribution of nodes is not uniform, there is no way to cover a large portion of the population unless large values of T can be handled. Thus the main examples of low angular velocity surveys are just two: one in GEO, where the resident GEO could be observed from an orbit which is nearly equatorial and nearly circular, with a period slightly smaller than one day; the other in MEO, where it is conceivable to launch a Space Based Surveillance System (SBSS) in (or near) one of the planes of a particular constellation asset (e.g. Galileo).

One basic property of both cases is clear: such a mission would be very effective for step 1) (discovery and early correlation), possibly even for step 2) confirmation, but there is no way to use it for step 3) orbit maintenance. This because the low relative velocity provides an extended period in which the observations are possible, without the need to manoeuvre the S/C attitude, but this advantage is paid by an extended period, even months, in which observations are no more possible. Although the argument in this special case is different, the qualitative conclusion is the same for all four orbital regions: there is no point in discovering objects which cannot be followed up from the ground.

4 SPACE-BASED GEOMETRY FOR SURVEY

In order to allow a proper correlation process followed by a preliminary orbit determination, at least two tracklets of the same object must be recorded from different points and/or ad different times. This can be obtained by exploiting a couple of S/C scanning the orbital belt to be detected. An advanced orbit determination process in fact [5] allows to reduce by one unit the conventional three S/C needed to obtain a set of three distinct and correlated observations as required by conventional orbit determination methods.

Beyond the advantage offered by advanced orbit determination techniques, the geometry of the observation plays a key role in improving the efficacy of the method, in fact using two satellites looking on the same object increases significantly the available information for its orbit determination.

In practice the concept foresees placing two satellites in the same orbit with a relative distance to each other allowing to observe in a dual correlated mode the portion of the orbital belt which must be subject to surveying. This way each S/C hosts a P/L suitable to observe a stripe of Sky with a well-defined shape (typically 5x15 sq. deg.) separated each other by a well-defined gap (typically 20 deg). This geometry can be defined as a 'correlating configuration'. The idea of a correlating configuration, depends also upon the software technology used. The classical methods for cold start correlation use three separate detections, with large enough spacing in time [6]. In the years 2000-2010 there has been a very substantial progress in correlation algorithms, as a result of dedicated mathematical research. There is now a list of known and well tested methods, with a significant literature. The most effective method, which was also the main tool of the extremely successful SARA simulation [2], is the one called "Keplerian integrals" [7]. A new generation method of this class has been published recently, with the possibility of improving by almost an order of magnitude the computational speed [8]. The basic idea is that all the detected trails are converted into 'attributables', with four measured quantities, corresponding to two angles and two angular velocity components. Then a couple of attributables are tested for the possibility of correlation, that is of belonging to the same orbiting object, by imposing four equations corresponding to integrals of the unperturbed 2-body problem (versions of the algorithm also accounting for precession due to J2 are already available). This way, correlation needs to be attempted not among all couples of attributables, but only among those with time difference of the order of few tens of seconds, to be extended to a few minutes for co-rotating objects.

4.1 Space observation major driving concepts

Referring to the concepts expressed in the previous chapters, the main system requirement for a Space based System which is competitive with a Ground-based sensor is the capability of obtaining two trails which can be immediately correlated. All previous studies have clearly shown that a space-based sensor obtaining at a single passage of a debris in the field of view too few observations for the computation of a full orbit cannot give a significant contribution to the required build-up of a Space debris orbit catalog. Of course a constellation of many SBSS could do this, but

then the number of satellites would be such that the cost cannot be competitive. Thus we have to assume as driving concept the one of a correlating configuration, specifically configured for this purpose with a suitable FOV. On the contrary the capability of tracking the already discovered debris, with all the timeliness requirement to maintain the orbit accuracy envelope, is not a driving concept, because the follow up observations from Space are not really needed, given the ease of performing tracking mode observations from the Ground, for objects down to ~3 times smaller in diameter d than the ones discoverable from the Ground.

The main parameter to be used to get a first approximation of a performance estimate is the angular velocity of the debris during one pass into the field of regard (which is the convex envelope of the FOV). This quantity of course also depends on the attitude control of the S/C, but for the moment we will assume that the S/C has a simple attitude and pointing of the telescope, such as zenith (stars are trailing in the field of view, but by an amount which can be managed by the same techniques used for observations of GEO from the ground). This assumption can be eventually relaxed, but it is anyway obvious that a large angular velocity of the S/C would give a significant disadvantage. The assumption of zenith pointing can also be relaxed, but it is correct as first approximation because it avoids stray light from the Earth and, when coupled with a sun-synchronous orbit, guarantees a phase of 90 degrees. Observations at lower phase are always possible (looking in a direction opposite to the Sun), but the distance to the shell containing the target population would grow more than the factor compensating the advantage in phase. Under these assumptions it is possible to build a "preliminary simulator" computing the apparent angular velocity on the image, given the altitude of the Space Based System orbit and of the debris orbit (both assumed circular), as a function of the angle between orbital planes (which coincides with the difference in the longitude of the ascending node for polar orbits). From the apparent angular velocity it is possible to compute the time to cross each portion of the dual correlated FOV, thus the probability of detection in either one or two portions, taking into account the time span between two images, which is limited by readout time of the CCD chips and by bandwidth availability for either transmission of the data or on board processing.

4.2   Selection of the target belt or belts

The next question is which are the orbital regions for which the concept of a Space based correlating configuration, to be coupled with Ground based tracking, can be eventually applied.

Thus we discuss some representative and possible Space based Survey missions for all orbital belts. For each of the four orbital regions around the Earth we assume a set of two S/Cs equipped with the same telescope type.

For low LEO we assume a Space based Survey System in a Sun-synchronous, nearly circular orbit at 600 km altitude, targeting the most densely populated shell around 800 km. For high LEO the same but at an altitude of 1200 km, targeting the densest group at 1400 km. For MEO we assume a Space based Survey System in a circular orbit near one of the Galileo constellation planes, at a lower altitude, as an example 22500 km. For GEO we assume an orbit plane near the equator, at an altitude of 35000 km. A detailed optimization of the observation strategy should be done for each of these missions, but as a starting point to fix ideas we are assuming a zenith pointing, with the FOV stripes observed by each S/C more or less parallel to the along track direction, separated by a 20 deg. gap and with a 5x15 sq. deg. rectangular shape. Further, exposures of 1 s for LEO, 10 s for MEO and GEO are considered; thus an image can be taken once every 5 s for LEO, every 15 s for MEO and GEO. The main parameter is the angle a between the orbit planes of the Space based System and of the observed debris. In all the figures we are showing only the range $0 < a < 180$ deg, because the figures are symmetric (with respect to the debris coming from the right/from the left). In the following figures we show the angular velocity (black curve, deg/s), the maximum angular velocity for a certain detection in the FOV stripes (red curve, deg/s), the probability of correlation, that is the probability that the trail appears on both stripes (assumed to be 5 degrees wide; green curve, #/#) and the magnitude loss due to the trailing factor T (assuming a pixel scale of 4.5 arcsec/pixel; blue curve, V_{mag}), as resulted for different orbital belts.
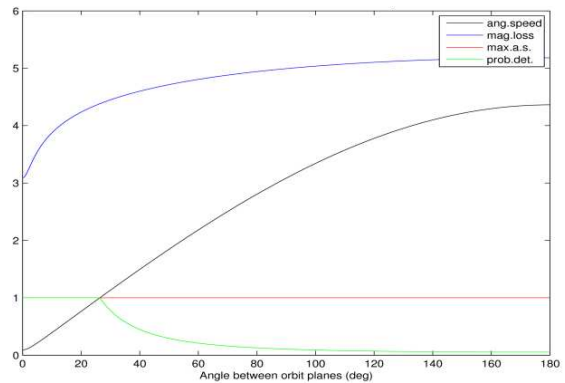

Figure 1. Observing strategy plot for a Low LEO mission, observing the main concentration of debris around 800 km of height from 200 km below, the units in the ordinate y-scale depend on the represented curves and are explained in the text.
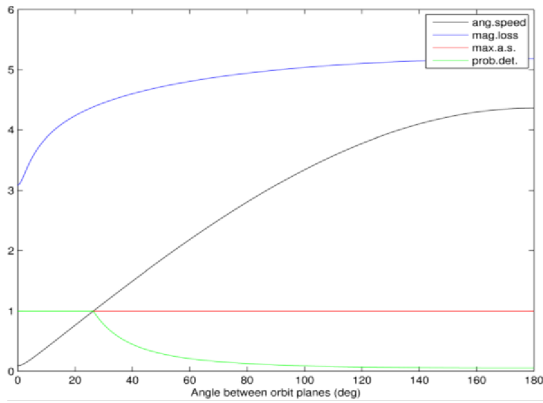
Figure 2. Observing strategy plot for a High LEO mission, orbiting 200 km below the densest group of LEO with altitude above 1000 km, which is around 1400 km, for y-axis units see Fig. 1 caption.
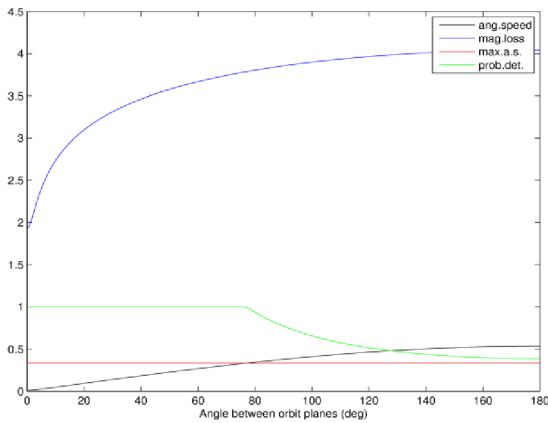

Figure 3. Observing strategy plot for a MEO mission, observing the region surrounding the Galileo constellation (from ~800 km below), for y-axis units see Fig. 1 caption.
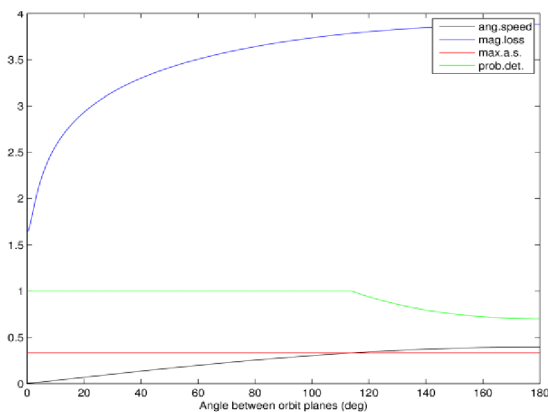

Figure 4. Observing strategy plot for a GEO mission, observing the geosynchronous belt from ~900 km below, for y-axis units see Fig. 1 caption.

If the orbit plane of the sensor is close to the equatorial one, the GEO objects with significant mass (excluding the very high A/M objects, which cannot be lethal) can only have inclinations up to 20 deg. Thus the correlation is certain and the magnitude loss due to trailing cannot exceed 3 magnitudes.

4.3   Summary of the obtained results.

Fig. 1, Fig. 2, Fig. 3 and Fig. 4 curves have been obtained with a very simple model, and have to be considered only as an indication of what is possible for the different orbit regions.

Still there are some interesting conclusions which can be drawn. The two regions of high-LEO and low-LEO can be observed under the same conditions from 2 different Space based Systems sensors, each orbiting about 200 km below the highest density shell in the two regions. A single Space based System, even in correlating configuration, cannot observe both regions with the same performances. For each shell, to build up a catalog including all orbital planes, a constellation with multiple S/C has to be used. Thus there are 2 very similar missions, which are very different from the point of view of the compliance with mitigation requirements. There is a strong indication that it could be possible to protect an entire orbital shell in MEO with a single Space based Survey System in correlating configuration, e.g., a System launched in one of the orbital planes of Galileo could protect all three planes. The protection with a single System of the entire enormous volume in space corresponding to the MEO region is of course not possible. Thus the main issue is the interaction among possible debris clouds generated by one navigation system with another navigation system, equally in MEO but at different altitude.

For a GEO application the observing conditions can be good for discovery and step 1 correlation, but the revisit time span for the same portion of the GEO belt is long (more than 1 month for the example of a 35000 km altitude S/C), thus confirming that there is no point for discovering a debris which cannot be followed up from the ground.

Tab.2 summarizes the discussion above for all meaningful Space based Survey Missions.

It is clear from Tab. 2 that a Space Based Survey System would be justified when objects smaller than those required for catastrophic collisions have to be monitored, with the possibility therefore to give a contribution to the knowledge of objects entering the lethality class problematic.

Table 2. Possible SBSS Missions scenarios, expected performances and related P/L dimensions. The second row reports the minimum diameter that can be tracked by one meter class telescope [2][3] from Ground once the object has been surveyed from Space, whereas the fourth row reports the corresponding Space Telescope entrance aperture necessary to survey the considered object

Orbital region	Low LEO h<1000 km	High LEO 1000<h<2000 km	MEO	GEO
Ground survey (min diam, cm)	5	8	30	40
Ground tracking and Space Survey Target (min diam, cm)	2.5	3	10	13
Number of S/C	8	8	2	2
Diameter P/L Primary Mirror (cm)	50	50	30	20-30

5   CONCLUSIONS

The reported work has to be considered a preliminary back to the envelop evaluation from which it results that a very viable approach to justify the application of a Space based System is in tight collaboration with a Ground Based asset.

Provided this fundamental assumption the conclusion of the above discussion can be summarized as follows:

- A very interesting and cost effective approach of designing an integrated ground/space system which is consistent with the requirement of creating and maintaining orbit catalogues is to use the space element to survey down to a size about 3 times smaller than the one for which discovery is possible with the ground-based survey,

- then follow up can be done in tracking mode from the ground with telescopes of the same class of the ground-based survey.

Further the results remarked that a Space Based Survey System, and in general a Space Based System, would be justified only when one has to monitor debris sizes smaller than those implied by catastrophic collision issues , opening a way to eventually contribute to the lethality issues category.

The presented results are the outcome of an internal study for new initiatives in the SSA domain and is expected to be hopefully further developed in the frame of a dedicated granted program, in order to investigate in detail and consolidate the fundamental aspects resulted from this work.

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